SINFONI's take on Star Formation, Molecular Gas, and Black Hole Masses in AGN

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Summary. We present some preliminary (half-way) results on our adaptive optics spectroscopic survey of AGN at spatial scales down to $0.085''$. Most of the data were obtained with SINFONI which provides integral field capability at a spectral resolution of $R \sim 4000$. The themes on which we focus in this contribution are: star formation around the AGN, the properties of the molecular gas and its relation to the torus, and the mass of the black hole.

1 The AGN Sample

The primary criteria for selecting AGN were that (1) the nucleus should be bright enough for adaptive optics correction, (2) the galaxy should be close enough that small spatial scales can be resolved, and (3) the galaxies should be "well known" so that complementary data can be found in the literature. These criteria were not applied strictly, since some targets were also of particular interest for other reasons. The resulting sample of 9 AGN is listed in Table 1. The observations of these are now completed, and while the data for some objects has been fully analysed, others are still in a preliminary stage. Additional AGN will likely be added once the Laser Guide Star Facility is commissioned.

One immediate result, which has a bearing on the classifications in the table, is the frequent detection of broad Brγ – i.e. with FWHM at least $1000 \, \mathrm{km \, s^{-1}}$. An example of this is given in Fig. 1. In only 3 galaxies was no broad Brγ detected: Circinus, NGC 1068, and NGC 1097 (in which even the narrow Brγ is so weak that it is almost lost in the stellar absorption features).

2 Star Formation

The topics we address here are the spatial scales on which stars exist around the AGN, the age and star formation history of these stars, and their contribution to the bolometric luminosity with respect to that of the AGN itself.

The stellar K-band (or equivalently H-band) continuum can be distinguished from the non-stellar continuum via the depth of stellar absorption

Table 1. AGN sample

Target	Classification	Dist. (Mpc)	Observations	
			Date	Instrument
Mkn 231[1]	ULIRG / Sy 1 / QSO	170	May '02	Keck / NIRC2
NGC 7469[2]	Sy 1	66	Nov '02	Keck / NIRSPAO
IRAS 05189-2524	ULIRG / Sy 1	170	Dec '02	VLT / NACO
Circinus[3]	Sy 2	4	Jul '04	VLT / SINFONI
NGC 3227[4]	Sy 1	17	Dec '04	VLT / SINFONI
NGC 3783	Sy 1	42	Mar '05	VLT / SINFONI
NGC 2992	Sy 1	33	Mar '05	VLT / SINFONI
NGC 1068	Sy 2	14	Oct '05	VLT / SINFONI
NGC 1097	LINER / Sy 1	18	Oct '05	VLT / SINFONI

[1] Davies et al. 2004a [2]; [2] Davies et al. 2004b [3]; [3] Müller Sanchez et al. 2006 [6]; [4] Davies et al. 2006 [4];
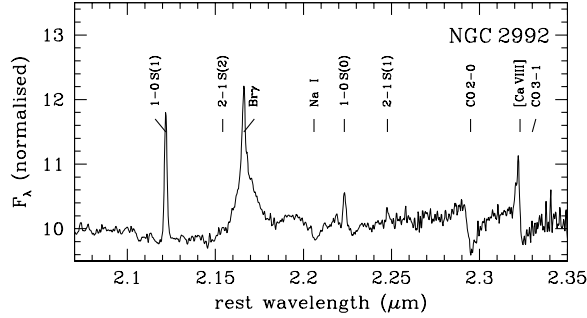

Fig. 1. Spectrum of the central $0.5''$ of NGC 2992, taken with SINFONI at a spatial resolution of $0.3''$ and a spectral resolution of $R \sim 3400$. The stellar absorption features are clear, as is the coronal [Ca VIII], the H_2 1-0 S(1), and both narrow and broad Brγ.

features such as the CO bandheads, because for any ensemble of stars the intrinsic depth will not vary much once late-type stars appear (see Davies et al. 2006 [4] for a more detailed discussion of this). Doing so immediately allows one to assess the physical size scale of the stellar population close to the AGN (see Fig. 2). In addition it permits a lower limit to be put on the bolometric luminosity originating in stars. This is because, while a stellar population which is still forming stars will have $L_{bol}/L_K \sim 50$ (or even higher if it is very young), even an old passively evolving population has $L_{bol}/L_K \sim 20$. In most cases we are able to apply tighter constraints than this by considering other diagnostics. For example, from the morphology and kinematics one can estimate the fractions of the narrow Brγ flux that are associated with stars and with the AGN's narrow line region. Similarly, it is often possible to estimate

the fractions of the radio continuum associated with the AGN and stars: the former will be unresolved and have very high brightness temperatures (see Condon et al. 1991 [1]). The ratio of either of these to the stellar K-band continuum can provide strong constraints on the star formation time scales and hence the bolometric luminosity from stars close around the AGN.

Our preliminary results are:

– In all 9 cases we have resolved a stellar population around the AGN on the scales we have achieved (0.08–$0.3''$); and the stellar luminosity increases as one approaches the AGN.
– In the 5 cases we have analysed in detail so far (Mkn 231, NGC 7469, IRAS 05189-2524, Circinus, NGC 3227), the stellar population is young: the range of ages we find is 40–120 Myr
– The (young) stellar luminosity is comparable to that of the AGN on scales of 1 kpc (Mkn 231, IRAS 05189-2524); is 10–50% of the AGN on scales of 50–100 pc (NGC 7469, NGC 3227); and is a few percent of the AGN on scales of 10–20 pc (Circinus).

3 Molecular Gas

The H_2 morphologies traced by the 1-0 S(1) line show a much greater diversity than the stellar distributions, as typified in Fig. 2. This might be expected since it is known that distribution of gas is strongly influenced by dynamical resonances and outflows. However, when analysing the morphologies on $\sim$10 pc scales, one needs to remember that the 1-0 S(1) line traces only hot (typically 1000–2000 K) gas, and hence the very local environment will have an important impact on the observed luminosity distribution: for example, is there a particularly massive star cluster nearby or has there been a recent supernova? With this caveat in mind, our preliminary results are:

– the 1-0 S(1) emission is stronger closer to the AGN (with the exception of NGC 1068) indicating the gas distribution is also concentrated towards the nucleus on scales of 10–50 pc.
– the kinematics show ordered rotation (again excepting NGC 1068) but also remarkably high velocity dispersion – in the range $\sigma = 70$–$140\,\mathrm{km\,s^{-1}}$, giving $V_{\mathrm{rot}}/\sigma \sim 1$. This means that the gas must be rather turbulent, most likely due to heating from the AGN and/or star formation, and as a result is probably geometrically thick.
– Given the size scales on which models predict the molecular torus around AGN should exist (10–100 pc, e.g. most recently Schartmann et al. 2005 [8]), and the fact that the torus must have a large enough scale height to collimate ionisation cones, it is reasonable to propose that the gas we have seen in these data is associated with the torus.
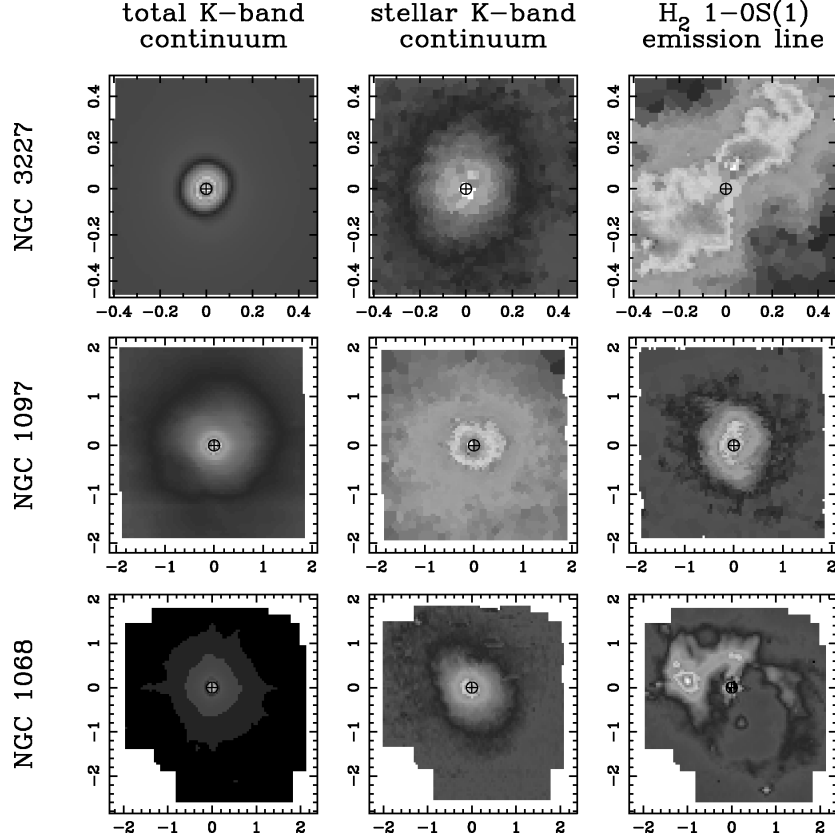
Fig. 2. Images from SINFONI of the 3 AGN NGC 3227, NGC 1097, and NGC 1068, which are at approximately the same distance so that $1'' \sim 70$–80 pc. The left panels show the full continuum at 2.1μm; the centre panels the stellar K-band continuum (derived from the CO bandheads); and the right panels the H_2 1-0 S(1) line emission.

4 Black Hole Masses

Since it was first discovered, the relation between the mass of the super-massive black hole M_{BH} and the velocity dispersion σ_* of the surrounding spheroid has become a cornerstone of galaxy evolution and black hole growth in the cosmological context. However, almost without exception the 'reliable' black hole masses (typically based on stellar kinematics and resolving the black hole's radius of influence) have been derived only for nearby bulge dominated E/S0 quiescent galaxies (see the review by Ferrarese & Ford 2005 [5]). While extremely challenging, it is therefore crucial to determine stellar dynamical black hole masses in AGN – not only to verify that the $M_{\mathrm{BH}} - \sigma_*$ relation holds for galaxies which are by definition active, but to assess its scat-

ter for these galaxies, and to provide a comparison to reverberation masses which might then allow one to constrain the geometry of the broad line region.

The high spatial resolution and integral field capability of SINFONI provide an ideal combination to do this, and we have successfully derived M_{BH} in NGC 3227 from stellar kinematics – the first time for a Seyfert 1 – using Schwarzschild orbit superposition techniques. Details of the specific code, which is based on that used by the Nuker team, are given in Thomas et al. (2004) [10]. While the inclination and mass-to-light ratios are often uncertain parameters, for NGC 3227 they are relatively well constrained. Nevertheless, we have explored the range of values which the modelling would permit and find it to be consistent with those expected, giving us confidence that the results are physically meaningful and reasonably robust. The resulting range of permissible black hole masses is $M_{\mathrm{BH}} = 5 \times 10^6$–$2 \times 10^7\,M_\odot$.

The range is a result of the degeneracy between the black hole mass and the 'effective' mass-to-light ratio of the stellar population, which includes the contribution of the gas mass. If the gas is significantly less concentrated than the stars, then the higher M_{BH} is possible; on the other hand if the gas is strongly centrally concentrated in a similar way to the stars, then M_{BH} must be correspondingly lower.

That the mass we find is within a factor of 2–3 of the masses found by other methods suggests that all are satisfactory to this level of accuracy. However, the fact that the mass is also likely to be a factor of a few below that implied by the $M_{\mathrm{BH}} - \sigma_*$ relation, while in contrast the stellar dynamical mass of Cen A (Silge et al. 2005, [9]) is a factor of several greater, may indicate that for AGN the scatter around this relation could be very considerable.

References

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